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A "sleeper" awakes: tidal current power

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Abstract

Tidal currents are formed by the energy dissipated by the tides. These can be thalassic, estuarine or fluvial. There has been a growing interest to harness these currents and turn the energy into electrical power. The potential is considerable. The technology is in existence or adaptable. The sites are numerous, though as with most ocean energies, only a small fraction of the global potential could be converted. The paper provides a brief review of an area that has been scrutinized for more than quarter of a century.

Keywords: Benefit–cost ratio; Potential; Sites; Tide-mills

Contents

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Only those who will risk going too far will find out how far one can go

1. Introduction

With at least 60 major papers in print and several international conferences on this subject since the last decade, it appears that, contrary to the assertions made in some trade-and-news journals, interest in tidal power—using barrages—is far from being on the wane [1,2–4]. This is particularly true in the Far East, viz. China, Japan, Korea [5].

Tidal power can be harnessed, as do tide mills, by creating a retaining basin and using the up and down movements created by the tides, or by diverting part of a flow and using the to and fro movements of the tide induced current, pretty much like a run-of-the-river approach [3: pp. 1–44, 4]. The flow of the tidal current is diverted in part into a channel where it turns a wheel. Some tide mills operate by tapping the energy of the tidal current [3,4,6]. Substitute a turbine, place it in the river's flow and you have a tidal current energy plant.

In discussions dealing with the extraction of tidal energy, tidal current power has been far less mentioned than tidal barrages; yet, this "sleeper" has been considered as a power source with a steadily increasing frequency for more than a decade [7–16]. As one may dispense with cofferdams, barrages, sluices and retaining basins, a tidal current power plant can be built and provide electricity far less expensively. Electricity production is of course more modest than with a "barrage plant". The view that tidal currents constitute a big saving compared to barrage schemes is not, however, held universally [17].

An advantage of the tidal current resource is that being gravitation bound, it is highly predictable; it is, however, not in phase with the solar day. One hundred and six locations in Europe if put in service would provide an exploitable 48 TW h/year [18].

2. Tidal current

The tide phenomenon is the periodic motion of the water of the sea—and is observed upstream of several rivers—caused by the celestial bodies, mainly the

moon and the sun. Tide results from the gravitational pull and the earth's rotation. Tide and tidal currents must be differentiated, for the relation between them is not simple, nor is it the same everywhere. In its rise and fall, the tide is accompanied by a periodic movement of the water, the tidal current, and the two movements are intimately related.

The current experienced at any time is usually a combination of tidal and non-tidal currents. Offshore, the direction of flow of the tidal current is usually not restricted by any barrier and the tidal current is rotary.

The tidal current is the rotary current that accompanies the crest of the turning tide in the open ocean and becomes a reversing current, near the shore, moving in and out, respectively, as flood and ebb currents. There is an instant or a short period—the slack period—when there is little or no current, at each reversal of current direction. During the flow in each direction, the current speed varies from 0 to a maximum—strength of flood or ebb—about midway between the slacks. The shore-wards, and upstream, movement is the flood and the seawards, and downstream, movement is the ebb.

Both the rise and fall of the tide, and the flood and ebb of the reversing current can be harnessed to produce mechanical and/or electrical power. Tidal currents alternate and their maximum velocity occurs at high and low water. The motion is uniform from surface to bottom, except for wave interference at the surface and it increases with distance. Because of the superimposition by other currents, the observation of tidal currents is difficult and requires extensive complex data.

Tidal currents may be semi-diurnal, diurnal or of mixed type, corresponding largely to the type of tide at the site, but often with a stronger semi-diurnal trend. The most common type is, to a greater or lesser degree, a mixed one.

When treating tides as waves, a progressive tide wave will have a shallow wave horizontal orbital velocity (U_s) as given by Eq. (1) wherein A is the wave amplitude, σ the angular velocity of a particle undergoing a circular motion as the tide wave passes by, k the wave number, h the water depth in which the wave is progressing, x the distance from a point of origin and t the time for a potential instant:

$$U_s = A\sigma/kh \cos(kx + \sigma t) \tag{1}$$

Tidal currents are an appreciable energy resource in relatively shallow water, near continents. When a particular geometry comes into play, the bottom and sides may impede the flow and speeds from 9 to 19 km/h have been registered.

2.1. Energy potential

Flow-of-the river potential is directly proportional to elevation above sea-level and precipitation run-off. If a "sector" is the distance between two successive confinements—about 10 km—the linear potential of a river is given in Eq. (2)

$$P_f = 9.8 \times Q_m \times H \tag{2}$$

wherein H is the elevation difference, expressed in meters, above sea-level, between the points of origin and exit of a sector, Q_m the mean discharge, expressed in m^3/s

at the end point of a section, and P_f the mean power expressed in kW. By summing up the successive P_f values ($\sum P_f$), a river's "potential" can be calculated.

The theoretical energy (E_f) is given by Eq. (3):

$$E_f = 8760 \Sigma P_f \tag{3}$$

2.2. Regional potential

To calculate $P_{f(region)}$ or linear potential for a specific region, one needs to know the elevation above sea-level of the individual basins (H_i) and the mean run-off of several basins. An estimate of the theoretical linear value of the per annum potential, in millions of kW h (kW h $\times 10^6$), is now possible (P_f). Taking H_{med} as the median of the H_i values, and V being the precipitations' run-off, expressed in millions of m^3, the potential is found through Eq. (5):

$$P_f = \frac{9.8 \times 8760 \times Q \times H}{8760 \times 360} \tag{4}$$

$$P_f = V \times H_{med}/367 \tag{5}$$

A region's potential can thus be given in kW h/km^2; but, in less developed countries particularly, it is often imprecise due to the lack of long-term hydrological data. As usual, the economic potential is lower than the theoretical potential for reasons such as several streams having too small a discharge or waters being diverted for irrigation. In some cases, not the "value" but the environmental constraints—natural or social—may make the implantation of a generating station unacceptable. The ratio between two values may well vary around 1–5. Finally, the economic potential value may vary in time.

Another estimation of extractable power (P_x), calculated in W/m^2, is given by Eq. (6) in which typical values of the extraction efficiency factor (μ), the velocity profile factor (K_s) and the spring/neap tide factor (K_n) are 0.25, 0.424, and 0.57, respectively; and w is the fluid density in kg/m^3.

$$P_x = \frac{1}{2} \mu w K_s K_n V^3 \tag{6}$$

$$P_x = 0.3 w V^3 \tag{7}$$

3. Geographical distribution of promising sites

Major tidal currents are encountered in the Arctic Ocean, the English Channel, Irish Sea, Skagerrak-Kattegat, Hebrides, the Gulfs of Mexico and St Lawrence, the Bay of Fundy, rivers such as the Amazon and Rio de la Plata, the Straits of Magellan, Gibraltar, Messina, Sicily, Bosporus. The tidal range is observed as far as 800 km upstream on the Amazon river! In the Far East, currents are encountered e.g. near Taiwan and the Kurile Islands. Northwest and Western Australia have their share. There are many other locations.

The more frequently cited examples are the Pentland Firth, Irish Sea North Channel, Alderney Race, Isle of Wight to Cherbourg, Orkneys to Shetlands. The

Florida Current has been mentioned repeatedly as it is assumed that it could provide 25 GW; but the idea of tapping it has raised more than an eyebrow among environmentalists.

Where narrow straits occur between land masses or are adjacent to headlands, large tidal flows develop. For instance, in the Iroise Sea, off the Brittany coast, current speeds of 8 knots are not infrequent in the Fromveur passage.

Very high one-way tidal currents exist in the Far East Indies and at the southeast of New Guinea-Papua. Indeed, the westerly movement of the "planetary tidal wave" increases substantially the southwesterly ebb flows in the connecting Pacific–Indian oceans' channels, with ebb tides reaching 10 knots in certain spots. An exploitable 70 TW h/year would be available in the Sibulu Strait of the Philippines [19].

Even if huge amounts of energy are available, it seems that the tidal current power is best adapted for regional, even local sites.

4. Proposed schemes

Twenty years ago, it was felt that a scheme most suitable for rentability—favorable benefit to cost ratio—would be the one in which rotors would be anchored, but suspended in mid-water—precisely to avoid wave influence—and let them drive hydraulic pumps, while conversion to electricity would occur at a central facility servicing several rotors. If these were spaced over some distance, the de-phasing due to tide variation would be compensated in partim. More turbines could be inserted into the system, an idea based on the belief that cost would be rather low.

Ten years ago, it was suggested anchoring a series of floating turbine and generator units in a line along the flow of the tidal current. A Savonius-type rotor might fulfill the role; however, due to the large size needed, a string of units would have to be stretched over at least half a kilometer. If the rotors drove hydraulic pumps instead, a hydraulic motor could combine each rotor's output, but then we would be back to the 1980s' proposal. Finally, as an alternate turbine-generator, a horizontal-axis free-stream machine could be used, though with a required diameter of 9-m.

Musgrove had felt that the most straightforward tapping scheme would be an underwater equivalent of a windmill. So has Heronemus [21]. Musgrove's scheme used vertical rotors.

5. A glance at the past and a look into the future

The tidal current was used by water mills on Evrepos Strait, in Cephalonia, in the floating tide mills on the Danube, Tiber, Seine and Russian rivers. A plant functioned briefly in northwestern Iceland and another has been mentioned in the Faroë Islands. The Danube tide mills have used undershot wheels since the Roman times to harness the tidal current. Some of them were still in use below the Iron Gate as late as 1970.

5.1. The modest forerunners

The term 'water mills' commonly designated run-of-the-river mills situated on waterways where there was/is no tidal current. The terms 'sea mill' and later 'tide mill' designated those mills that took advantage of the tides with or without retaining ponds. There were thus tide mills that took advantage of the ebb and/or flood current. Some such mills were even "dual-powered". Tidal current mills operated on one of the two systems: they were equipped with a single wheel that rotated with the current between two pontoons, or the mill consisted of a single pontoon with a wheel attached to each side, similar to the approach with paddle-wheelers.

The Dunkirk (Dunkerque, France) "Perse mill" (end of the 17th century to 1714), the Bacalan mill a few kilometers north of Bordeaux on the Gironde River, and the El Ferol mill (Galicia, Spain) used an ingenious hydraulic machinery that allowed them to use both ebb and flood currents for power production [20]. So could the scheme installed in the Thames river under the London Bridge. The Demi-Ville (Morbihan Department, France) was an example of dual-powered mill using both the fluvial current and the tidal currents.

5.2. The contemporary scene

Tidal river energy can be tapped both in the sea environment and in tidal rivers and streams. Its potential is large and a mere 10% of the energy in Great Britain was estimated to be sufficient to provide more than 5% of the country's electrical needs a quarter of a century ago [21]. The 8-knot current of the river underneath the Golden Gate Bridge (San Francisco) can provide all the bridge's needs for electricity. Likewise, were the Florida Current to be harnessed, 25 GW of electricity could be produced. An "aqua power barge", capable of "harvesting" energy along coasts and on tidal rivers, proposed in 1979, would use a high-impulse low-head turbine. With a 6-knot current, 50 kW of installed power could be produced (Fig. 1).

Patents have been taken out in the United States since the 19th century for a variety of devices intended to tap the energy of waterways directly; they encompass small units as well as "giant" paddlewheels. AeroVironment Inc., where the Coriolis Project was developed[1], examined the river energy resource for the western United States, the economics of ducted un-ducted axial-flow turbines and even carried out some small-scale rotor model tests [22] (Fig. 2).

Davis and Swan sought to develop a ducted Darrieus design [23,24]. Designs of non-conventional conversion systems have been frequently reviewed (Pratte, Davis, and others) [9,22–24]. Vertical axis turbines were proposed by Davis and Swan [23,24].

A technology assessment conducted by New York University on behalf of the State of New York [23,24] and dealing principally with the tapping of the tidal current in the East River in New York city, yielded information on a number of

[1] A project that examined a scheme to tap the Florida Current.

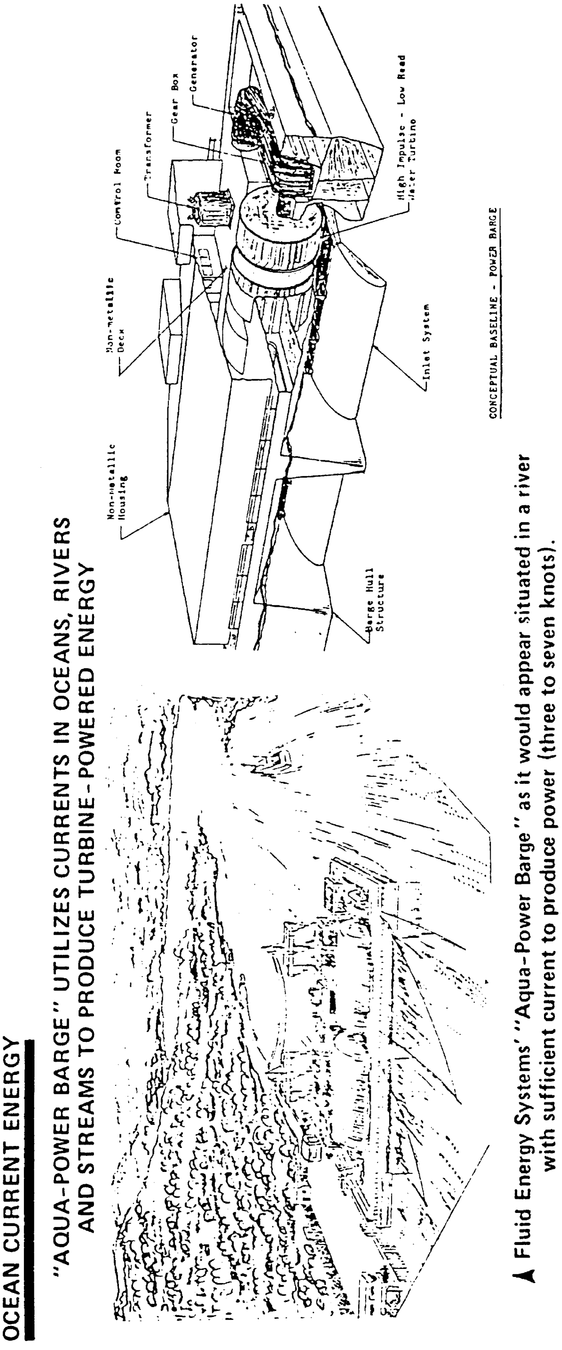

Fig. 1. Artist's view of the Aqua Power barge.

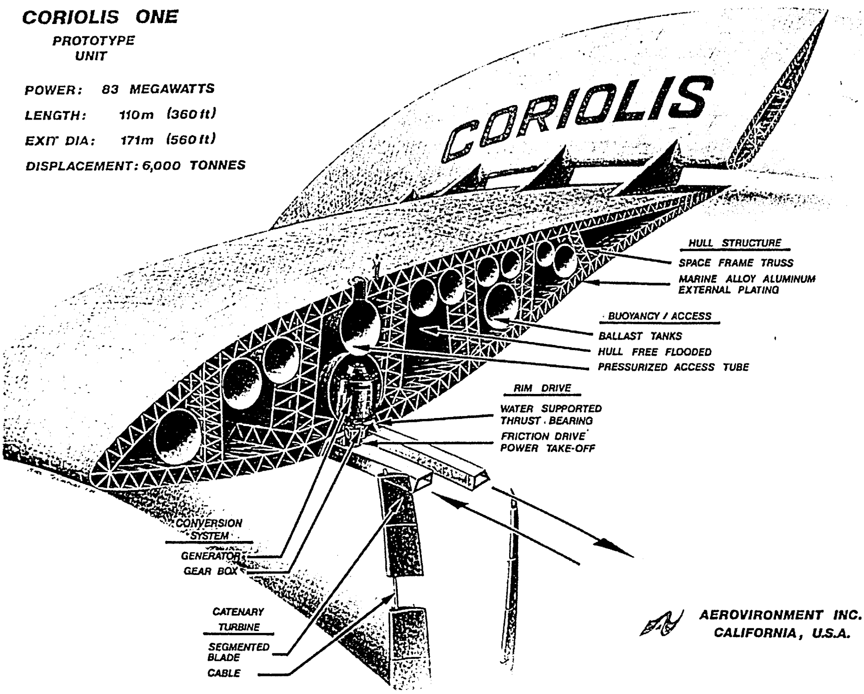

Fig. 2. The Coriolis device as proposed by AeroVironment.

devices which could be used and examined the advantages of axial-flow propeller machines [25–31]. The various types of KHECS[2] included waterwheels, free-ducted and Wells rotor axial-flow turbines, Darrieus, Savonius, and cyclo-giro type vertical axis rotors and the Schneider Lift Translator. The conclusion of the studies was that the system would cost less than US$ 1700 per kilowatt installed[3].

A prototype was installed in the East River's semi-diurnal Eastern Channel in 1985 (Fig. 3).

Attached to the side of a bridge, the 4.3 m diameter device used a three-blade conformal design. Modest ducts had been attached to the screen hoop to test their potential cost-effectiveness. The unit was dismantled for inspection after a short period of operation.

Though there are hardly any tidal current schemes, many proposals have ventured to link various seas, streams and canals. Some visionaries, including Theodore Herzl in 1902[4], have suggested a canal linking the Dead and Mediterranean

[2] Kinetic hydro energy conversion systems.
[3] In terms of US$ in 1980.
[4] In his novel "*Altneuland*".

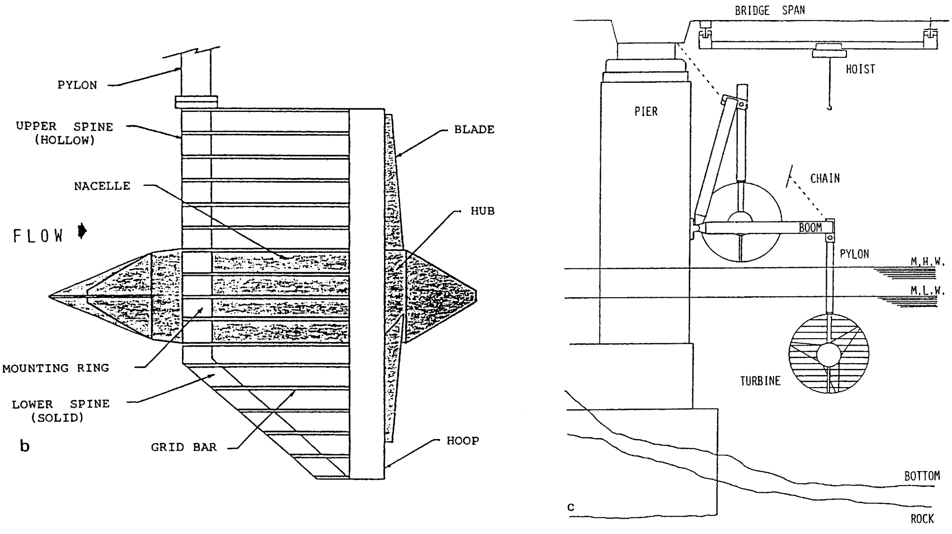

Fig. 3. The East River tidal river scheme for New York city.

Seas, and proposed to tap the current to generate electrical power. Some thoughts to that effect had been expressed as early as 1850. It was however the James Hayes Commission which, in 1943, made the first assessment. An Israeli commission recommended moving ahead with a linking project at the end of the 1970s [32,33]. Apparently, the plan has been laid to rest, probably better so in view of the probable ecological consequences it would have.

The advantages of the *Turbodyne Generator* were praised in 1982: the amount of turbine material is small and the high speed vertical-axis turbine was shown in theory and actual tests were performed. It was seen that power generation is possible, in ebb and flow tides, independent of the current speed, provided the current has a small head (even <1.5 m), siltation risks are low, environmental impact rather benign and no sluices are necessary.

Baker and Wishart conducted a study covering three small estuaries and 17 sites in Great Britain and, in terms of 1983 dollars, arrived at a cost varying between US$ 6.10 and 6.30, depending on the number of turbines per kW h. The cost (C) of a barrage is given in Eq. (8), which includes correction factors for shallow margins and ranges ≤ 1

$$C = \frac{L^{0.8}(H+2)^2}{A(R-1)} \tag{8}$$

wherein L is the length of a barrage, H is maximum depth, A is the basin area and R is the tidal range [34,35].

Among the recommended sites were the Camel River (Cornwall), the Taw-Torridge estuary (Devonshire), Milford Haven (South Wales), Loughor Estuary and several on the Mersey River [36,37].

The Salford Transverse Oscillator could harness energy from tidal currents e.g. in rivers and tidal inlets; it could function in basins as small as 0.5 km^2, e.g. the Loch Heuran (Scotland). Installation of a prototype was considered in 1993. If P is power, ω the specific weight of water, Q the water discharge, H the head, then

$$P = \omega QH \tag{9}$$

When the flow becomes as little as 0.49 m/s, an immersed Savonius type rotor driving a generator could power a marine beacon, and greater efficiency could be attained by channeling it through ducts. Grant has discussed the potential use of the tidal flow for navigation buoys [38].

The concept of the so-called dynamic dams has also been proposed for tidal streams [39].

5.3. Current developments

The various turbine rotor options are, as has been mentioned for some time, quite similar to those for wind turbines, the horizontal axial-flow turbine and the Darrieus or cross-flow turbine. In the latter type, the blades rotate perpendicular to the flow.

Options to secure a rotor include mounting the unit beneath a floating pontoon or buoy, suspending it from a tension leg arrangement between an anchor on a seabed and a flotation unit on the surface (as has been proposed in the past), or seabed mounting, easy only in shallow environments [40].

5.4. Seaflow and Optcurrent

Canada is implementing a 250 kW demonstration plant [41] but Great Britain is installing and grid-connecting a 300 kW horizontal axis turbine [42]. The latter is a Joule Program project code named ‘‘Seaflow’’. The ‘‘Optcurrent’’ project is likewise a Joule Program undertaking involving the Robert Gordon University and the University College of Cork, besides IT power.

The Seaflow project utilizes a Lynmouth turbine, a horizontal axis system mounted on a rigidly fixed vertical pillar, while the Stingray (see below) involves a linear lift based device which relies on the same operational physical principles.

5.5. Stingray

The ‘‘Stingray’’ project is underway (Fig. 4). A feasibility study had been started in August 2001 and a prototype generator has been immersed off the Shetland Islands in Yell Sound, in 36 m deep water. Costing close to US$ 3 million (€ 2.56 million), the generator weighs 180 metric tons; the 150 kW device was financed in part by the British government’s Department of Trade and Industry. It was assembled on-shore along the Tyne river.

Due to the current’s predictability, the electricity can be marketed under the existing pool management regime free of under- or over-provision risk.

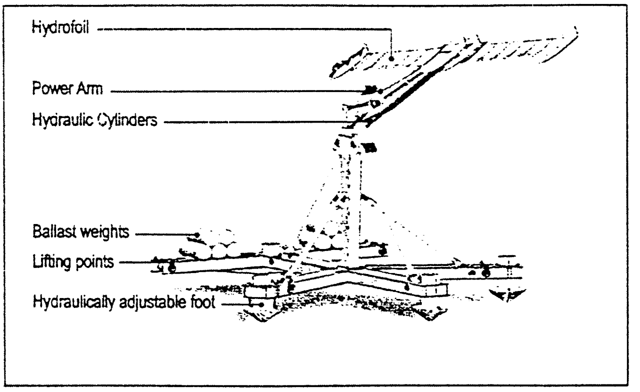

Fig. 4. The Stingray device.

Stringray had a predecessor, the AWCG, a tidal stream device that used the current flowing over hydroplanes to lift a chamber up, and let it down, at the surface of the water[5]. The air in the chamber was alternately drawn in and expelled through a generator driving the rotating turbine affixed on top of the chamber. The oscillating hydroplane principle was retained, though the hydroplanes are mounted on a completely submerged structure. Tidal current action on the hydroplanes initiates the oscillating motion that directly operates hydraulic cylinders. The cylinders act on high pressure hydraulic oil that drives the generator. Seabed positioning protects the device from storms and insures that it does not interfere with navigation. An environmental impact assessment was conducted.

The hydroplane is 15 m wide and is installed at 20 m above the sea bottom. The structure is 24 m high. A yaw mechanism keeps the hydroplanes aligned with the flow of water through ebb and flow. A peak hydraulic power of 250 kW was matched by a time average output of 90 kW in a 1.5 m/s measured current. A repeatable 45 kW output was attained in a 1.7 m/s current speed.

Cost-wise, a price of 8–30 US¢ (6.4 to 24 € cents[6]) is foreseen; technological improvements will probably lower the price of the kWh.

The machine is due to get an improved hydroplane control and a new configuration. Retrieved in late 2002, the newer Stingray version has been scheduled for redeployment during 2003 for a longer period of operation. A correct grasp of the resource and the effects of placing multiple devices in service should be known later in the year. According to the company involved—Engineering Business Ltd—a simultaneous program to start the installation of a 5 MW version, connected with local power grids, is scheduled for July 2004.

Still in the Shetlands area, Scotland benefited from the European Union Regional and Urban Energy Programme [43]. Small islands would be happy reci-

[5] Active column water generator (ACWG).

pients of the electricity generated from ocean sources, e.g. Vlieland (see further below). In this project, actual measurements were computer fed and, for two sites, the ensuing mathematical model showed that load factors of around 50% could be reached for 15 m–200 kW turbines rated for tidal current speeds of 2 m/s. Including installation and grid connection, costs would run close to € 920,000 (US$ 1,076,400[6]) for turbines with a minimum life-span of 15 years; electricity could be produced at a price of € 0.123 (US$ 0.144) per kW h. With theoretically eight turbines of 20 m diameter, a price of less than € 0.74 (US$ 0.87) per kW h would be reached.

5.6. Vlieland and the Electricité de France

The French electricity provider company, Electricité de France, through an intermediate subsidiary, has proposed that the island of Vlieland, in the Dutch province of Friesland, to be the location for one of its demonstrations of renewable energy projects. Among the technologies is a 2 × 2 tidal current turbine, consisting of two pillars, each with two rotor blades. The pillars would be anchored to the seabed. The blades, 15 m wide, would rotate 18 h a day generating a total of 1400 kW. A collateral benefit would be coastal protection.

The project itself would combine tidal current, wind turbines, and hydrogen and fuel cells. Electrolytic hydrogen would be produced using surplus energy, a way to store power or to load fuel cells for public transport.

If the plans materialize, Vlieland would become the first island in the world where all the power would be generated by and stored in exclusively renewable sources.

5.7. In the Arctic

The world's most northerly town, Hammerfest, in Norway, will be the first city to obtain its electrical power from a submarine station run by tidal currents. The 200 metric ton turbine is anchored on the seabed near Kvalsund. Its current capacity is 3 MW but it is to increase to 20 MW by 2004. The production would suffice to supply the needs of 1000 homes. Costs have already reached US$ 6.7 million (€ 5.73 million)[6] and by the time the entire project is completed, it should have had a price tag of US$ 14 million (€ 11.97 million)[6]. The cost of the produced electricity at US$ 0.04–0.05 (€ 0.034–0.043)[6] is however triple that of hydroplant produced power in Norway.

This tidal power will be integrated to the electricity mix in the local grid. The turbine is similar to a wind turbine. The current speed is 2.5 m/s.

A risk factor is involved as storms have wrecked ocean power stations before. The success of the undertaking could transform Hammerfest into a tidal turbine manufacturing center.

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[6] Exchange rate of May 2003.

6. Conclusion

Studies have been conducted at Garolim, Korea and the Messina Strait in Italy. In Canada and Russia, the Darrieus type turbine has been in favor for some time. It remains nevertheless that often plans have been laid to rest because of a major drawback, the low-energy density. All things being equal, the energy from a tidal current is one or two orders of magnitude lower than that from a turbine of the same diameter in a barrage. It is felt by some that the disadvantage wipes out the savings provided by dispensing with engineering works.

This author does not stand alone in lamenting that objections are continuously raised to slow down the development of alternate ways to produce electrical power.

Commercial exploitation will have to solve the problems derived from water either too deep or too shallow [44]. The technology to be developed is likely to be based upon buoyant tethered systems and not fixed seabed approaches [45,46].

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